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The three tasks undertaken during the final portion of this grant are the modeling of frontal instabilities, coastal flows generated by river outflow, and Indian-Ocean physics and biology. Two papers have been published on frontal instabilities. In Fukamachi, McCreary and Proehl (1995, *JGR*) we examined the dynamics of the small-scale frontal instabilities, finding that they are primarily ageostrophic baroclinic instabilities (AGBIs). In Yu, McCreary and Proehl (1995, *JPO*) we argued that tropical instability waves (TIWs) resulted primarily from AGBIs. A remarkable aspect of most of our river solutions is that the outflow bends *to the left* as it emerges form the river mouth, instead of bending to the right as in the typical case; a paper describing this research (McCreary, Zhang and Shetye, 1996, *JPO*) is currently under review. In the field of Indian-Ocean research, we developed a coupled physical/biological model that can simulate remarkably well the annual variability of both physical and biological variables in the Arabian Sea, and a paper describing this research is in press (McCreary, Kohler, Hood and Olson, 1996, *Prog. Oceanogr.*). We also examined the causes of the annual variability of the East India Coastal Current in two papers: Shankar, McCreary, Han and Shetye (1996, *JGR*), and McCreary, Han, Shankar and Shetye (1996, *JGR*).

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NOVA SOUTHEASTERN UNIVERSITY

September 25, 1996

Dr. Manuel Fiadeiro
Physical Oceanography
Code 1122ML
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5560

Dear Dr. Fiadeiro:

This letter is the final report for ONR Grant No. N00014–90–J–1054. This grant began on October 1, 1989, and a number of projects were added to it over the years. Jeffrey Proehl and I were the principal investigators on the final project, entitled "Numerical studies of oceanic processes. Part 1: Frontal instabilities, meridional cells, river runoff, and Indian-Ocean studies." Its duration was from March 1, 1994, to August 28, 1996, and the total award was $289,546. There were three parts to the project. I describe our accomplishments in each part in the remainder of this letter.

Frontal instabilities: Two papers have been published describing our research on frontal instabilities. In Fukamachi, McCreary and Proehl (1995, JGR) we reported a theoretical study of the small-scale frontal instabilities (wavelengths of the order of 20 *km*) that are prevalent in coastal upwelling regions and elsewhere. The abstract from that paper follows:

> The instability of density fronts is investigated as a possible generation mechanism for the small-scale, wavelike patterns that are commonly observed along upwelling fronts and filaments. Unstable-wave solutions are obtained in two linearized models: a $1\frac{1}{2}$-layer model, and a continuously stratified model confined to the surface region of the ocean. The background state in the layer model consists of vertically oriented isotherms associated with a depth-independent current, whereas in the continuously stratified model it consists of steeply tilted isotherms and a vertically sheared current.
>
> Solutions are found both when the background velocity field V is zonally uniform and when it is zonally sheared. When V is weak and zonally uniform, approximate solutions are derived analytically for both models that are valid for low-frequency, low-wavenumber waves. These solutions demonstrate that the unstable waves in the two systems are dynamically related, both being representations of ageostrophic baroclinic instability. Numerical solutions corroborate the analytic results and extend their range of validity. Energetics analyses confirm that the energy source for the waves is the background potential energy associated with the zonally varying T field. When V is a zonally sheared jet, the models still exhibit a band of instability, which is identifiable

with ageostrophic baroclinic instability. The most unstable wave in this band has a short wavelength, a frequency near $f/2$, and a rapid growth rate consistent with observed features.

In Yu, McCreary and Proehl (1995; JPO), we argued that the primary energy source for tropical instability waves (TIWs) was a frontal instability like that described above, rather than barotropic instability as is commonly believed. The abstract from this paper is:

One of the striking features of TIWs is that they appear to be more prominent north of the equator. A linearized, -layer ocean model is used to investigate effects of various asymmetric background states on structures of equatorial, unstable waves. Our results suggest that the meridional asymmetry of TIWs is due to asymmetries of the two branches of the South Equatorial Current (SEC) and of the equatorial, sea-surface-temperature (SST) front; it is not due to the presence of the North Equatorial Countercurrent. Energetics analyses indicate that frontal instability associated with the equatorial, SST front, as well as barotropic instability due to shear associated with the SEC, are the energy sources for the model TIWs.

River outflow: Shuliang Zhang (one of my graduate students), Satish Shetye and I have investigated the effects of river outflow on coastal circulation using variable-density, $1\frac{1}{2}$- and $2\frac{1}{2}$-layer models. A remarkable aspect of most of our solutions is that the outflow bends *to the left* as it emerges from the river mouth, rather than flowing to the right as in the typical case. Indeed, this behavior also occurs in many GCM solutions of river outflow. We have submitted a manuscript describing the dynamics of leftward bending in our solutions to JPO, and the abstract follows:

A variable density, $1\frac{1}{2}$-layer model is used to investigate the dynamics of the fresher-water plumes generated by river outflow. Solutions are found in a north-south channel, with the transport M_r and salinity S_r of the outflow specified as boundary conditions along a 25 km-wide segment of the western boundary. In most cases, the river water discharges into a pre-existing, oceanic mixed layer with thickness H_1.

When M_r is sufficiently low, plumes remain coastally trapped. Immediately after the outflow is switched on, a coastal Kelvin wave is excited at the river mouth that establishes a southward current of oceanic water along the right-hand coast. In contrast, all the river water first bends to the left as it exits the river mouth, and the resulting plume advances northward along the left-hand coast. At the plume nose, some of the fresher water reverses direction, and this water, together with some oceanic water, flows southward on either side of the offshore density front between the fresher and salty waters. Two processes cause this upstream movement: geostrophic adjustment generates the southward frontal current, and Kelvin-wave propagation from the nose thins the layer within the plume thereby establishing the northward, geostrophic, coastal jet.

When M_r is sufficiently high, plumes expand offshore indefinitely. If the Rossby number of the outflow is also large enough, the river water flows directly offshore and

only a portion of it recirculates to form a northward-propagating coastal plume. The angle at which the outflow leaves the river mouth becomes more southward as M_r and S_r increase and as H_1 decreases.

The strength of the northward-propagating plume is weakened as H_1 decreases and S_r increases. When $H_1 = 0$, so that there is no ambient oceanic layer, there is no northward plume at all. Likewise, the plume is weakened when the model includes entrainment, a process that acts to prevent the layer thickness from thinning appreciably.

The remainder of this research project is described in Shuliang's thesis, of which he has recently completed a first draft. Among other things, his thesis discusses solutions to the $2\frac{1}{2}$-layer model, and the influences of background currents and winds on river plumes.

Indian-Ocean research: During the past few years, our major achievement in this field was the development of a coupled physical/biological model of the Arabian Sea that can simulate remarkably well the annual variability of both physical and biological variables there. We expect our solutions to provide theoretical support for the recent JGOFS and ONR field work in the region. This research is described in McCreary, Kohler, Hood and Olson (1996, *Prog. Oceanogr.*, in press). The abstract from this paper is:

A coupled, physical-biological model is used to study the processes that determine the annual cycle of biological activity in the Arabian Sea. The physical model is a $2\frac{1}{2}$-layer system with a surface mixed layer imbedded in the upper layer, and fluid is allowed to move between layers via entrainment, detrainment and mixing processes. The biological model consists of a set of advective-diffusive equations in each layer that determine the nitrogen concentrations in four compartments: nutrients, phytoplankton, zooplankton and detritus. Coupling is provided by the horizontal-velocity, layer-thickness, entrainment and detrainment fields from the physical solution. Surface forcing fields (such as wind stress and photosynthetically active radiation) are derived from monthly climatological data, and the source of nitrogen for the system is upward diffusion of nutrients from the deep ocean into the lower layer. Our main-run solution compares favorably with observed physical and biological fields; in particular, it is able to simulate all the prominent phytoplankton blooms visible in the CZCS data.

Three types of blooms develop in response to the physical processes of upwelling, detrainment and entrainment. Upwelling blooms are strong, long lasting events that continue as long as the upwelling does. They exist during the Southwest Monsoon off Somalia, Oman and India due to coastal alongshore winds, and at the mouth of the Gulf of Aden due to Ekman pumping. Detrainment blooms are intense, short-lived events that develop when the mixed layer thins abruptly, thereby quickly increasing the depth-averaged light intensity available for phytoplankton growth. They occur during the fall in the central Arabian Sea, and during the spring throughout most of the basin. In contrast to the other bloom types, entrainment blooms are weak because entrainment steadily thickens the mixed layer, which in turn decreases the depth-averaged light intensity. There is an entrainment bloom in the central Arabian Sea during June in the solution, but it is not apparent in the CZCS data.

Bloom dynamics are isolated in a suite of diagnostic calculations and test solutions. Some results from these analyses are the following. Entrainment is the primary nutrient source for the offshore bloom in the central Arabian Sea, but advection and recycling also contribute. The ultimate cause for the decay of the solution's spring (and fall) blooms is nutrient deprivation, but their rapid initial decay is due to grazing and self shading. Zooplankton grazing is always an essential process, limiting phytoplankton concentrations during both bloom and oligotrophic periods. Detrital remineralization is also important: in a test solution without remineralization, nutrient levels drop markedly in every layer of the model and all blooms are severely weakened. Senescence, however, has little effect: in a test solution without senescence, its lack is almost completely compensated for by increased grazing. Finally, the model's detrainment blooms are too brief and intense in comparison to the CZCS data; this difference cannot be removed by altering biological parameters, which suggests that phytoplankton growth in the model is more sensitive to mixed-layer thickness than it is in the real ocean.

We have also examined the dynamics of the annual variability of the East India Coastal Current (EICC). One motivation for this study was the property that during the spring the EICC reverses to flow northward *against* the prevailing winds of the Northeast Monsoon. Three hypotheses have been advanced to explain this reversal: remote forcing from the equator (J. J. O'Brien and coworkers), remote alongshore winds along the eastern and northern boundaries of the Bay of Bengal (McCreary), and wind curl in the interior of the Bay (Shetye). This research is described in detail in two papers: Shankar, McCreary, Han and Shetye (1996, JGR), and McCreary, Han, Shankar and Shetye (1996, JGR). The abstract from the second paper follows:

A linear, continuously stratified model is used to investigate the dynamics of the East India Coastal Current (EICC). Solutions are found numerically in a basin that resembles the Indian Ocean basin north of 29°S, and they are forced by *Hellerman and Rosenstein* [1983] winds. Effects due to the following four forcing mechanisms are isolated: local alongshore winds adjacent to the east coasts of India and Sri Lanka, remote alongshore winds adjacent to the northern and eastern boundaries of the Bay, remotely forced signals propagating from the equator, and interior Ekman pumping.

Each process contributes significantly to the EICC surface flow at some locations and at some times during the year. Along the Indian coast (north of 10°N), the surface EICC flows northeastward from February until September, with a strong peak in March-April and weaker flow from June to September; interior Ekman pumping, remote alongshore winds and equatorial forcing all contribute to the springtime peak, whereas local alongshore winds are the primary driving force of the weaker summertime flow. Along Sri Lanka (south of 10°N) the surface EICC flows northward only during March and April; the absence of northward flow at other times is due to interior Ekman pumping which drives a strong southward current for much of the year (April to December). Along both coasts there is southward flow from October to January that is driven by interior Ekman pumping and local alongshore winds.

The EICC also has significant subsurface flow on several occasions. Along the Indian coast, there is southwestward flow extending to depths greater than 1000 m from May to July that is driven primarily by equatorial forcing. From July to September, the southwestward flow forms a shallow subsurface counterflow (a Coastal Undercurrent); its cause is primarily equatorial forcing and interior Ekman pumping, not the local alongshore winds as might be expected.

Finally, Weiqing Han (graduate student) and I have made considerable progress in adding salinity to the Indian-Ocean model. Shetye (1991, *priv. comm.*) has pointed out that the mixed layer is usually shallow (or even absent) in the Bay of Bengal, in contrast to our wintertime solution which has a deep mixed layer in the northern Bay. The likely reason for this lack is the intense rainfall and river runoff in the Bay, which inhibits entrainment by lowering the density of the mixed layer. We have modified the formulation of entrainment in the model to include the effects of salinity on density, and our initial solutions corroborate this hypothesis. This research will be included as part of Weiqing's thesis research, and hopefully published within the next year.

Sincerely,

Julian P. McCreary, Jr.

cc: Barbara Sterry, NSU Contracts and Grants Officer